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Effects of Age of Acquisition and Word Frequency on the Processing Bias of the Middle/Inferior Frontal Gyrus

Yaqiong Xiao, Hongchang Zhai*, Xiaoxia Xu
College of Education, Guangzhou University, Guangdong, 510006, R.P. China
*Corresponding author, E-mail address: zhaihongchang307@gmail.com

(**Abstract**) As early as the year 2000, researchers had found that the activation peak of Chinese processing was in the middle part of the left frontal lobe (BA9); this area was less activated in studies of alphabetic writing; and even when there was activation, it was very weak. Since then, many Chinese studies have also reported activation in the left inferior frontal gyrus. However, the purpose of this research has mainly been focused on the semantic and phonological function of the middle frontal gyrus. The current study addressed the effects of the age of acquisition (AOA) and word frequency on the processing bias of the middle/inferior frontal gyrus using the homophone judgment task based on the high and low frequency Cantonese and Mandarin Chinese characters. The results showed that during homophonic judgments of high-frequency Cantonese characters, the left inferior frontal gyrus was activated; tasks with low-frequency Cantonese as well as high- and low-frequency Mandarin activated the left middle frontal gyrus (BA9 / 6). These results suggest that early developed, native spoken language is processed in the left inferior frontal gyrus, while late developed, written language is processed in the left middle frontal gyrus in a manner dependent on the AOA and not the frequency. These results also show that the functional correlations between the left inferior frontal gyrus, the middle frontal gyrus and the right hemisphere depend on the task and that different tasks involve different networks of functional correlation in the left or right hemisphere.

Keywords: Cantonese; Mandarin; High Frequency; Low Frequency; Age of Acquisition; FMRI.

1. Introduction

How frequency and age of acquisition (AOA) affect the processing of brain areas has aroused widespread interest among researchers.

The research into the influence of word frequency on the processing of brain areas has revealed that high-frequency words consistently activate the left inferior frontal gyrus, and the brain areas activated by low-frequency words are very different. Most studies of low-frequency Chinese characters have found activations in the left middle frontal gyrus, while the alphabetic writing of both high- and low-frequency has generally activated the left inferior frontal gyrus. Studies including those of Fiez et al. (1999) and Chee et al. (2002) found that the brain areas activated by high- and low-frequency English word tasks were not different for native English speakers; both consistently activated the left inferior frontal gyrus (BA44), the superior temporal gyrus etc. Some study results have shown that the alphabetic writing of both high-and low-frequency activated the left inferior frontal gyrus, but the location was slightly different (Chee et al., 2003; Fiebach et al., 2002). In the study of Lee et al. (2004), activations in response to high-frequency words in left inferior frontal gyrus were significantly lower than those of low frequency words. In contrast to alphabetic writing, high and low frequency Chinese words activated processing in different brain areas. Using a naming task with high- and low-frequency Chinese characters, Kuo et al. (2001) reported that high-frequency Chinese characters more strongly activated the bilateral inferior parietal lobe, and low-frequency words more strongly activated the left precentral gyrus (BA6), left superior frontal gyrus/SMA (BA6) and so on.

There are basically two views regarding the effects of AOA on language processing brain areas. The first states that the cognitive processing of two languages in the brain is not affected by AOA; that is, the brain areas activated by two languages will not be significantly different if one language was acquired early and one was acquired late. Klein et al. (1994) asked English (L1)-French (L2) bilinguals to perform word repetition tasks while undergoing PET scanning. Their results showed no differences in brain activation patterns between tasks, except in the left putamen, although L2 was acquired late (after 5 years old). Chee et al. studied Chinese (L1)-English (L2) bilinguals and reported no differences in language processing brain areas at the level of words (Chee et al., 1999b) or sentences processing (Chee et al., 1999a), regardless of if L2 was learned early (before 6 years old) or late (after 12 years old). The authors speculated that the

different activations had no relationship to the order in which participants learned their languages or the age at which L2 was acquired. Yokoyama et al. (2006) reported the same language functions for the left inferior frontal gyrus, middle/superior temporal gyrus and parietal cortices for L1 (Japanese) and L2 (English). The other opinion is that the age at which L2 is acquired decides the brain area localization of L2. For early bilinguals, the processing areas of the two languages tended to be in the same brain areas, and both languages showed activations in the left inferior frontal gyrus (Kovelman et al., 2008; Perani et al., 2003; Tham et al., 2005). When L2 is acquired late, its processing is different from that of L1, which activates the left middle frontal gyrus (Isel et al., 2010; Kim et al., 1997; Perani et al., 1996). However, some studies have reported activation of the inferior frontal gyrus for both early and late acquired languages (Hernandez et al., 2007).

It is inadequate to merely focus on word frequency or AOA. The early behaviorists have put forward the following criticisms of studies of word frequency and AOA. First, because high-frequency words include both early words acquired before pre-school and late acquired words, some researchers pointed out an uncontrolled age factor in the previous studies; the frequency effects in the word recognition tasks were likely caused by uncontrolled AOA factors, rather than frequency. For example, Gilhooly and Logie (1981) found that AOA had an independent influence on reaction time in word naming but no influence on frequency. A study by Morrison and Ellis (1995) showed that time differences in word naming reflect the age at which the materials were learned, and there are no differences across groups with different lexical frequency. Second, the frequency effect exists in word cognitive processing. The AOA effect is probably caused by lax control of the frequency of early and late words. Similarly, both AOA and frequency affect the recognition of a word (Barry et al., 2001; Brysbaert, 1996; Fiebach et al., 2003; Gerhand and Barry, 1998, 1999a; Morrison and Ellis, 2000).

In short, word frequency and AOA have a close relationship. Early (e.g., pre-school) learned words (except baby-talk) are generally high frequency words. Late learned words include both high- and low-frequency words. Some high-frequency words are likely to be learned early and some are likely to be learned late. Generally speaking, low frequency words are acquired late. Combining frequency with AOA will facilitate the study of their influences on word processing brain areas.

Fiebach et al. (2003) explored the effects of AOA and word frequency in conditions that controlled for other variables. The results showed that the brain activation's adjustment to AOA was not affected by word frequency. Word frequency mainly adjusted the activation of the inferior frontal gyrus, but the effects of AOA were more spread out; they simultaneously adjusted the activation of the precuneus, temporal lobe and inferior frontal areas. Therefore, in the process of word cognition, there are not only identical brain areas that are affected by AOA and word frequency, but there are also brain areas specifically affected by AOA. Weekes et al. (2008) pointed out that the effects of AOA and frequency on brain activation are independent of each other. Hernandez and Fiebach (2006) compared fMRI data acquired from early and late word tasks across word frequency conditions and did not find any brain areas that were more strongly activated in the early word task than the late word task; however, they found that the front-middle part of the left temporal lobe was more strongly activated by late acquired words than early acquired words. However, Ellis et al. (2006) reported that when frequency (Log frequency of name: early: M = 0.92, SD = 0.42 late: M = 0.92, SD = 0.35) was held constant, early words activated the left precuneus (BA18), superior temporal gyrus and bilateral middle occipital gyrus much more strongly than late words. Compared to early words, late words led to stronger activation in the left middle occipital gyrus (BA19) and the fusiform gyrus (BA37). Thus, the authors thought the stronger activations by early words suggested that early words have more detailed visual and semantic information processing associated with them compared to late words, and the stronger activations by late words have increased difficulty in indication of semantically processing these words for the visual form.

As can be seen in previous studies, the ranges used to define high-frequency and low-frequency words have lacked statistical standards and spanned great differences. Some have defined high-frequency alphabetic writing as 145 per million words (Fiez et al., 1999), some as 59 per million words (Chee et al., 2002) and for some, the average was 149.45 per million words ((Fiebach et al., 2002). In a study of Chinese character frequency, Tan Xiangjie et al. (2004) defined Chinese characters used 1000-2000 times/million words as high-frequency words and words used 50-100 times/million as low-frequency words. Also, some researchers have defined high-frequency words as those used over 400 times/million words and low-frequency words as those used under 50 times/million words (Kuo et al., 2003; Lee et al., 2004). Some researchers have even defined words used over 253 times/million words as high-frequency words (Peng et al., 2003).

These are also differences in how early and late acquisition is defined. The following are different schemes that have been used to define AOA: ① the 7 scale method, in which participants are asked to subjectively judge at what age they acquired a word on a scale from 1 to 7 (1 = before 2 years old, 2 = 3-4years old，3 = 5-6 years old，4 = 7-8 years old，5 = 9-10 years old，6 = 11-12 years old，7 = after and 13 years old) (Fiebach et al., 2003); ② participants are asked to decide the exact age of acquisition of the word (Ghyselinck et al., 2000); and ③ words are defined by the percentage of age at which people can properly understand the word's semantics (Ellis et al., 2006; Bonin et al., 2001). These methods are too subjective, and make it hard for participants to decide the exact age at which a word was learned. In addition, several standards

exist for the division of early and late AOA: Weekes et al. (2008) defined 3.8 years old as early and 6.5 years as late; Ellis et al. (2006) defined the under 4 as early and 4-12 as late; some have defined under 6 as early（Chee et al., 1999）, and over 12 as late（Hernandez et al., 2007). There is no agreed upon standard for the division of age. We think the age that brain processing appears separation should be taken as the division of age.

Combined with the normal age of school attendance, the current study used the age division of Chee et al., which defined under 6 years old as early and over 12 years old as late. To separate the effects of AOA and word frequency, we recruited native Cantonese participants who learned Mandarin until school age, and selected high and low frequency words of Mandarin and Cantonese from a percentage rank database. The participants were asked to perform a homophone judgment task with two runs during the scanning. In addition to show the brain areas activated in each task, we also explored the functional correlations among the activated brain areas of each task. In the study, we aim to address the effects of AOA and word frequency on the processing biases and networks of the middle frontal gyrus and inferior frontal gyrus.

2. Experimental procedures

2.1 Participants

Twenty-five students from Guangzhou University took part in the experiment. To avoid the practice effect, they were divided into two groups, thirteen of whom (5 male, 8 female) participated in the behavioral study, while the rest (6 male, 6 female) participated in the fMRI scanning. Participants ranged from 18 to 21 years old, and all were right handed. All participants were native Cantonese speakers who began studying Mandarin in elementary school and, thus, were considered late Mandarin learners. The results of a Mandarin Proficiency Test demonstrated that they were fluent in Mandarin speaking and listening. Informed consent was obtained from each subject prior to scanning.

2.2 Materials

We choose high- and low-frequency words in the following manner: word frequency was transformed into a percentile rank, then words above the 80^{th} percentile were taken as high-frequency words, and words below the 20^{th} percentile were taken as low-frequency words. The words learned before school were selected from high-frequency words by native Cantonese students and teachers at a nursery school, and late words learned after 12 years old (Grade 4 of elementary school) were selected from low-frequency words.

In this study, participants were native Cantonese students, also late learners of Mandarin. In the study, early high-frequency and late low-frequency characters were separately selected from Cantonese and Mandarin. As the majority of Cantonese and Mandarin characters are identical but different in pronunciation, thus, in fact, Mandarin early high-frequency words were mastered before school attendance, although their pronunciations were learned after elementary school. Forty-five characters were selected from Cantonese and Mandarin, and then paired, 30 pairs of which were homophones, while 15 pairs were not. The frequency of high-frequency words was higher than 1200 times/million, while frequency of the low-frequency words was lower than 30 times/million. The percent rank and numbers of characters are listed in Table 1, and part of Mandarin and Cantonese pronunciation experiment materials are listed in Table 2.

2.3 Procedures

The experiment used a block design with two scanned runs (a high- and low-frequency run). Each run included six task blocks that were an alternating arrangement of three blocks of each language condition. Each block consisted of 15 trials that included 10 pairs of homophones and 5 pairs of characters with different pronunciations. The duration of each trial was 33 seconds. Trials were presented in the following manner: one character was displayed above a fixation cross and one was displayed below the fixation cross. This display lasted 1500 ms and was followed by the fixation cross alone for 500 ms. Two Chinese characters arranged up and down were presented as a baseline; they were displayed for 2100 ms. Participants were asked to judge whether the presented characters were homophones. Each run lasted, in total, 5 minutes and 45 seconds, see Fig. 1.

2.4 Behavioral Experiment

Details of the experimental task have been described above, which was similar with the task settings inside the scanner. Thirteen participants performed the behavior measurement to determine the performance of native Cantonese speakers when judging high/low-frequency Cantonese and Mandarin words. The procedure were running by E-prime 2.0 software (Psychology Software Tools, Inc. www.pstnet.com/eprime), and participants were asked to press key as response. Finally, response times were collected from the experiment.

2.5 fMRI data acquisition

The experiment was performed with participants in a Philips Achieva 1.5T NOVA DUAL MR scanner. Two-dimensional structural images were scanned using a fast spin echo (FSE) sequence, T1*-weighted images and horizontal slices. The following scan parameters were used: TR/TE=2507 ms/15 ms, slice thickness = 5 mm, gap = 0 mm, slice number = 30, field of view (FOV) = 230 mm×230 mm, matrix = 384×512. Functional scans were obtained using a T2*-weighted gradient- echo planar imaging (GRE-EPI) sequence with horizontal slices. The following scan parameters were used: TR/TE = 3000 ms/50 ms, flip angle = 90°, slice thickness = 5 mm, gap = 0 mm,

FOV = 230 mm×230 mm, matrix=64×64, and the whole brain was scanned with 30 slices. High-resolution three-dimensional anatomical images were acquired with a T1*-weighted fast low angle shot (FLASH) sequence with axial slices (TR/TE = 25 ms/4.1 ms, flip angle = 35◦; slice thickness = 1.1 mm, gap = 0.26 mm, 160 slices; FOV=230 mm×230 mm; matrix = 256×256).

2.6 Data analysis

Date preprocessing. Preprocessing of fMRI data was performed using AFNI (Analysis of Functional

Table 1. Percent rank distribution of Cantonese and Mandarin characters

	high-frequency				low-frequency					
percent rank	85	90	95	100	5	10	15	20	25	30
numbers of Cantonese	6	33	28	23	10	12	16	16	24	12
numbers of Mandarin	6	37	26	21	13	14	14	16	21	11

Table 2. Mandarin and Cantonese pronunciation experiment materials

Cantonese high frequency						**Mandarin high frequency**				
character	鱼	墙	路	脚	线	花	脸	树	图	猪
Mandarin	yu2	qiang2	lu4	jiao3	xian4	hua1	lian1	shu4	tu2	zhu1
Cantonese	jy4	tsoeng4	lou6	goek8	sin3	faa1	lim5	sy6	tou4	dzy1
Meaning	fish	wall	road	foot	line	flower	face	tree	picture	pig
Cantonese low frequency						**Mandarin low frequency**				
character	蚁	巫	蕊	貂	栈	痣	辕	崖	盔	蛆
Mandarin	yi3	wu1	rui3	diao1	zhan4	zhi4	yuan2	ya2	kui1	qu1
Cantonese	ngai5	mou4	joey5	diu1	dzaan6	dzi3	jyn4	ngaai4	kwai1	tsoey1
Meaning	Ant	carline	pistil	ermine	inn	beauty	thill	cliff	casque	maggot

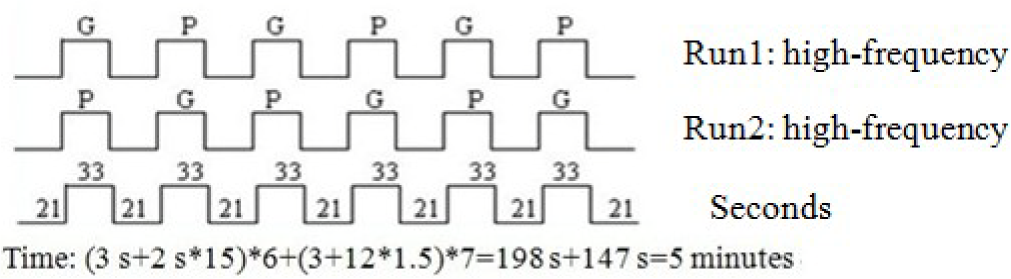

Fig. 1. Experiment design (G: Cantonese，P: Mandarin)

NeuroImages, AFNI) software (Cox, 1996). Images acquired from the first two scans were excluded. The fMRI images were first adjusted for slice timing, realigned, and spatially smoothed (FWHM=5 mm). Next, the rate of signal change in the functional MRI data was calculated, and data were normalized. Finally, functional MRI images were aligned and spatially normalized to structural MRI images, and images were resampled into 3 mm×3 mm×3 mm cubic voxels in the same standard coordinates.

ANOVA analysis. Total activations in response to high- and low-frequency Cantonese and Mandarin words were analyzed with 3dANOVA program. We used the residuals as parameters and corrected the activation images with the 3dFWHMx, 3dClustSim program. The voxel volumes greater than 1728 mm^3 ($F>3.26$, $P<0.01$) activated in all four tasks were retained.

Functional correlation analysis. In addition to general preprocessing, signals were averaged, detrended, and ROI

masks were drawn based on the brain areas activated in the four conditions.

Then, text data of the time course signals under different conditions were extracted with 3dbucket, 3dcalc, and 3dmaskave. Correlation statistics were calculated with SPSS 18.0, and network pictures were drawn based on areas of high correlation.

3. Results

3.1 Behavioral results

Before fMRI scanning, behavioral experiment was performed by 13 participants using the same experiment procedures. And then the reaction times data were analysis with SPSS 18, Release Version 18.0.0 (SPSS, Inc., 2009, Chicago, IL, www.spss.com). The results indicated that, for high-frequency words, reaction times were faster for Mandarin than Cantonese (Cantonese-Mandarin $t(12)=5.22$, $p<0.05$), while there was no difference in reaction times between low-frequency Cantonese and Mandarin words (Cantonese-Mandarin $t(12)=-1.01$，$p>0.05$).

3.2 fMRI results

Brain areas activated during the four tasks

Twelve native Cantonese speakers participated in homophone judgment tasks with high- and low-frequency Cantonese and Mandarin words. ANOVA was used to analyze the coordinates of activated brain areas. For the brain areas activated during the homophone judgment tasks across the four conditions, see Table 3, Fig. 2 and Fig. 3.

As shown in the below activation pictures, low-frequency Cantonese and both high- and low-frequency Mandarin tasks activated the left middle frontal gyrus. Our subjects learned Mandarin and low-frequency Cantonese characters late. We found that the left middle frontal gyrus was responsible for the processing of late acquired language and words. Both high- and low-frequency Mandarin activated the middle frontal gyrus, showing that late acquired language was processed there. The processing areas depended on AOA, rather than the frequency. The early high-frequency words of Cantonese activated the left inferior frontal gyrus, which indicates that the inferior frontal gyrus processed early language. High-frequency words of Cantonese and Mandarin activated different brain areas, proving that the inferior frontal gyrus activation was dependent on AOA. See Table.3, Fig. 2 and 3.

Correlation of brain areas activated by low-frequency words and correlation of brain areas activated by high-frequency words

To explore the functional correlation among the activation brain areas of each task, brain areas activated in four tasks were separately drawn as ROIs. And then the maximum values over the time courses within the ROIs were analyzed as correlation matrix statistics. Correlations higher than 0.7 were taken as highly related brain areas.

The following are the correlation coefficients between brain areas activated in the high-frequency Cantonese word task that were greater than 0.7: 0.77 between the left inferior frontal gyrus and the right superior frontal gyrus: 0.87 between the left declive and the right cerebellar tonsil; 0.79 between the left declive and the right declive; and 0.77 between the right cerebellar tonsil and the right declive. The left inferior frontal gyrus and the right superior gyrus displayed high correlations, and the lateral cerebellums were highly related.

The following are the correlation coefficients between brain areas activated during the low-frequency Cantonese word task that were greater than 0.7: 0.85 between the left lingual gyrus and the right fusiform gyrus; and 0.74 between the left middle frontal gyrus and the right medial frontal gyrus.

The following are the correlation coefficients between brain areas activated during the high-frequency Mandarin word task that were greater than 0.7: 0.80 between the left middle frontal gyrus (BA9) and the right medial frontal gyrus; 0.75 between the left middle frontal gyrus (BA9) and the left middle frontal gyrus (BA6); 0.87 between the left lingual gyrus and the right declive; 0.72 between the left lingual gyrus and the right lingual gyrus; 0.75 between the right declive and the right lingual gyrus; and 0.70 between the right medial frontal gyrus and the left middle frontal gyrus (BA6).

The following are the correlation coefficients between brain areas activated during the low-frequency Mandarin word task that were greater than 0.7: 0.82 between the left lingual gyrus and the right fusiform gyrus; and 0.71 between the left middle frontal gyrus and the right medial frontal gyrus.

The highly related brain regions in the frontal lobe were the following: the left inferior frontal gyrus activation in the high-frequency Cantonese word task is highly related to the right superior frontal gyrus; the left middle frontal gyrus activation during the low-frequency word tasks is highly correlated with the right medial prefrontal lobe; the high- and low-frequency Mandarin tasks both produced strong relationships between the left middle frontal gyrus and the right medial prefrontal lobe. These results demonstrated that the processing network for Chinese is different from that for alphabetic writing in that the Chinese processing network typically showed joint processing

Table 3. Coordinates of brain areas activated in high- and low-frequency homophone judgment tasks of Cantonese

frequency	L/R	Brain area	BA	Volumes	Peak(X，Y，Z)		
Cantonese Low frequency	L	Lingual gyrus		13419	-25.5	-79.5	-9.5
	L	Middle Frontal gyrus	9	12825	-40.5	10.5	35.5
	R	Fusiform lobe	19	7290	25.5	-67.5	-9.5
	R	Medial Frontal gyrus	8	3996	1.5	40.5	38.5
	R	Culmen		3969	7.5	-55.5	2.5
	R	Fusiform gyrus	20	2052	43.5	-31.5	-24.5
	L	Cerebellar Vermis		1782	-1.5	-31.5	-36.5
	L	Middle Frontal gyrus	6	1782	-37.5	-1.5	50.5
Mandarin low frequency	L	Lingual gyrus	18	6480	-22.5	-79.5	-9.5
	L	Middle Frontal gyrus	9	4671	-34.5	7.5	38.5
	R	Fusiform gyrus	19	4428	28.5	-73.5	-12.5
	R	Medial Frontal gyrus	9	3429	16.5	25.5	32.5
	L	Caudate		1917	-19.5	25.5	8.5
Cantonese high frequency	L	Inferior Frontal gyrus		16389	-40.5	28.5	2.5
	L	Declive		15093	-28.5	-67.5	-18.5
	R	Cerebellar Tonsil		11880	37.5	-52.5	-33.5
	R	Superior Frontal gyrus	6	9396	7.5	19.5	59.5
	R	Declive		7479	1.5	-79.5	-15.5
	R	Middle Frontal gyrus		2214	28.5	40.5	-0.5
Mandarin high frequency	L	Middle Frontal gyrus	9	10530	-43.5	13.5	35.5
	L	Lingual gyrus		10071	-19.5	-76.5	2.5
	R	Claustrum		7614	25.5	16.5	20.5
	R	Declive		6075	28.5	-76.5	-15.5
	R	Medial Frontal gyrus		5400	7.5	16.5	47.5
	R	Lingual gyrus		2160	1.5	-67.5	-0.5
	L	Cingulate gyrus		1890	-13.5	10.5	32.5
	L	Middle Frontal gyrus	6	1836	-37.5	-1.5	53.5

Note. L/R refers to the left or right hemispheres of the brain; Brain area, the activated areas of the brain; BA, Brodmann's area; Volumes, the activated volume sizes; Peak (x,y,z), coordinates in the Talairach & Tournoux space.

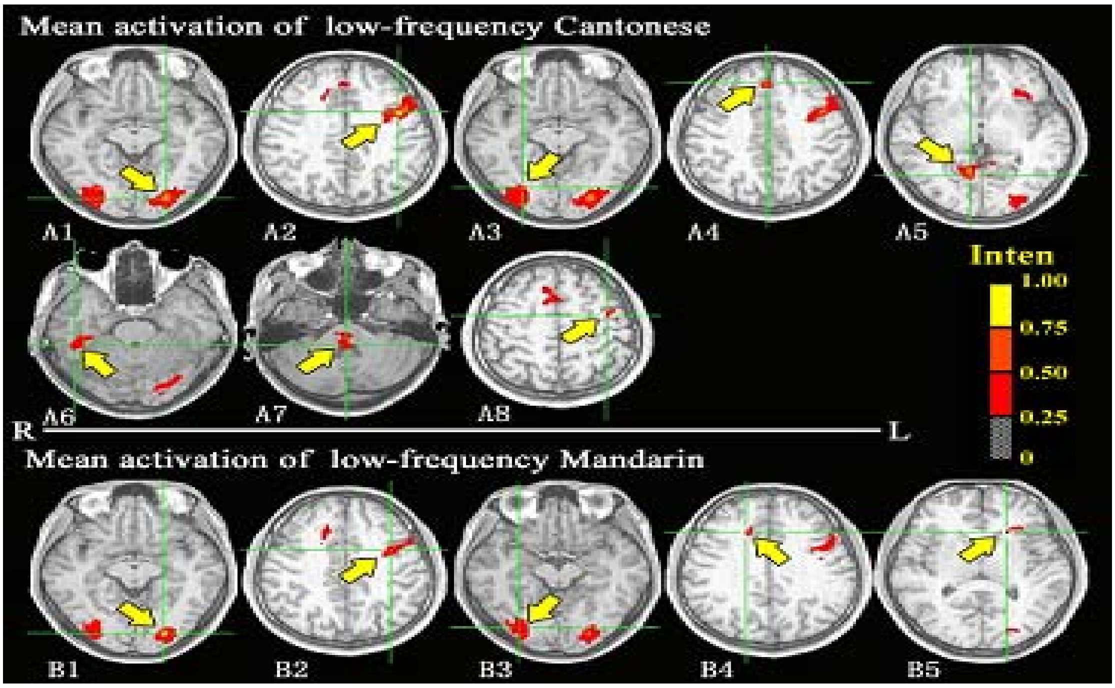

Fig. 2. Activation picture for low-frequency Cantonese and Mandarin.

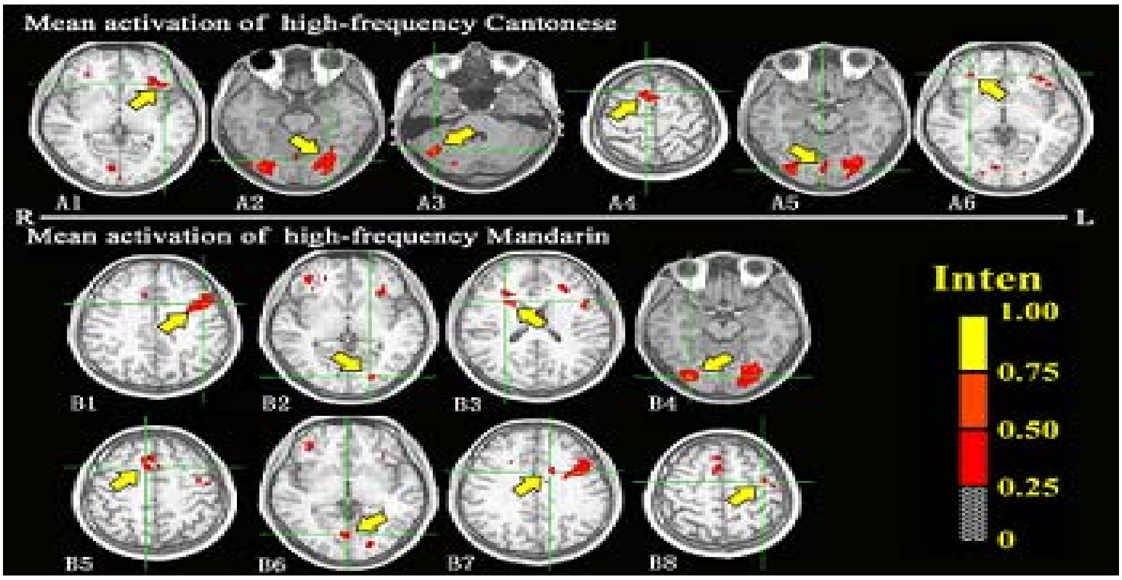

Fig. 3. Activation picture for high-frequency Cantonese and Mandarin

across hemispheres. High levels of functional connectivity are available between the right superior frontal gyrus and the left inferior frontal gyrus and between the left middle frontal gyrus and the right medial prefrontal lobe. A figure illustrating the correlations (>0.7) across brain areas is shown in Fig. 4.

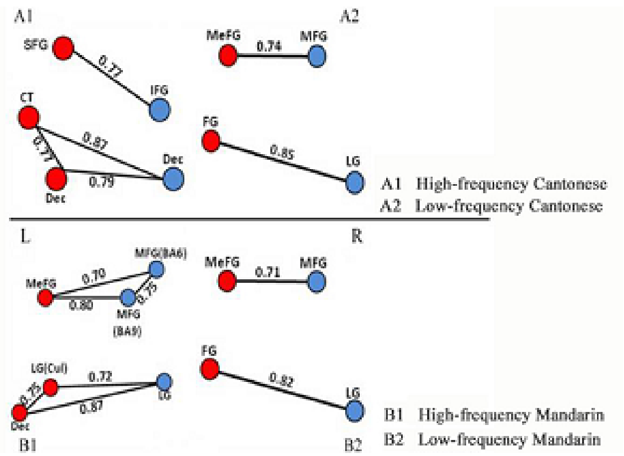

Fig.4. Correlation networks between brain areas activated during high- and low-frequency Cantonese and Mandarin word tasks.

4. Discussion

The present study proved the following:

Firstly, the left inferior frontal gyrus processes early acquired words, and the left middle frontal gyrus processes late acquired words; this division is based on AOA, rather than word frequency.

The relationships among word frequency, AOA and activations in frontal areas are shown in Fig. 5.

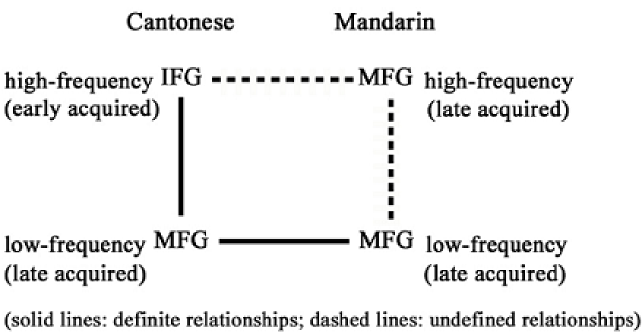

Fig. 5. Inferior /middle frontal gyrus activation compared with word frequency and AOA.

High-frequency Cantonese activated the inferior frontal gyrus (IFG), and low-frequency Cantonese and high/low-frequency Mandarin words activated the middle frontal gyrus.

The following discussion is organized according to the four lines in Fig. 5. High- and low-frequency Cantonese: high-frequency early words have the characteristics of oral language, while low-frequency words share features with late acquisition and written language. The high-frequency Cantonese word task activated the left inferior frontal gyrus and the low-frequency word tasks activated the left middle frontal gyrus. Therefore, the left inferior frontal gyrus has a bias toward processing of early, oral language, and the left middle frontal gyrus processes late, written language. Cantonese low-frequency words—Mandarin low-frequency words: both types of words activated the left middle frontal gyrus, which provides further proof that the left middle frontal gyrus processes late written language. Mandarin high-frequency words—Cantonese high-frequency words: although both are categories of high-frequency words, they are processed in different brain regions. Cantonese high-frequency words were acquired early, but the phonology of Mandarin high-frequency words was acquired late. Therefore, the division of the left inferior frontal gyrus and the left middle frontal gyrus is not based on frequency, but AOA. That is, compared to frequency, AOA plays a

more central role.

There are several different theories about the mechanism of AOA based on behavioral studies. One is the phonological completeness hypothesis, which holds that words learned early are much more comprehensive in phonological output than words learned late. Late learned words are indirectly represented phonologically, and thus, more time is required to produce phonological output (Brown and Watson, 1987). The growing network model is another theory. It provides a different interpretation from the perspective of semantic processing. This theory holds that the acquired order of conception is a very important factor for the development of the semantic system. The conception of late acquired words is defined based on that of early acquired words (Brysbaert et al., 2000a, 2000b). In the present study, the division between the middle frontal gyrus and the inferior frontal gyrus supports the late AOA theory (Brysbaert et al., 2000; Gerhand and Barry, 1999b).

We believe that the organization of the brain has spatial and temporal characteristics. That is, the ideology of time and space in philosophy is still suitable for brain organization. The brain organization of language processing and storage is in accordance with time. The early brain organization in childhood does not have any stored language signal, making it easy to accept phonology and semantics and allowing better integration between these components. After a certain age, the space of the inferior frontal gyrus would have already been occupied by acquired language. Therefore, late acquired language and the phonology of alphabetic writing are separated into the temporal lobe for processing; Chinese characters are separated into the left middle frontal gyrus for processing. We speculate that the left inferior frontal gyrus may have been the first brain area to develop for oral processing, while the left temporal lobe and the left middle frontal gyrus are both functional expansions of the left inferior frontal gyrus.

That the left inferior frontal gyrus and the left middle frontal gyrus process different objects has been proven in previous studies on AOA. For example, Isel et al. (2010) examined early and late high-familiarity France-German bilinguals. The results showed that the peak values of activation in early bilinguals were in the left inferior frontal gyrus (BA47), while those for late bilinguals were in the left middle frontal gyrus and other brain areas. Perani et al. (2003) found that both languages of early (3 years old) bilingual subjects consistently activated the left middle/inferior frontal gyrus, and the right inferior frontal gyrus.

Generally speaking, low-frequency Chinese characters are late acquired. Activation of the middle frontal gyrus by low-frequency words is also supported by previous studies. Lee et al. (2004) asked native Chinese subjects to read low-frequency Chinese characters. The findings showed that the main area of activation was in the middle frontal gyrus (BA6). Kuo et al. (2003) also reported activation of the left middle frontal gyrus in a low-frequency Chinese character task. These findings have lead researchers to believe that the middle frontal gyrus processes the unique features of Chinese characters and coordinates phonic output.

Secondly, there are obvious differences between the brain areas processing Chinese characters and alphabetic writing, and these differences come from late acquired words and low-frequency words. Early acquired words, like alphabetic writing, are processed in the left inferior frontal gyrus.

In the study of Tan et al. (2000), subjects were required to finish a verb production task. The results found that the activation peak for processing Chinese was in left the middle frontal gyrus (BA9). The activation of this region has rarely been reported in previous studies of alphabetic writing, and when it has, it has been only weak activation. Using a variety of semantic distinction tasks, Weng et al. (2003) found that the left middle frontal gyrus and bilateral parietal lobes were activated in Chinese processing tasks, and the intensity and volume of the activation were both regulated by the difficulty of the task. The semantic judgment tasks of early English-Chinese and late Chinese-English bilinguals of Chee et al. (2001) showed that the left inferior frontal gyrus was strongly activated by processing of unfamiliar language. Fiez et al. (1999) reported activations that included the left inferior frontal gyrus during a low-frequency English word naming task. The authors speculated that the activation in the left inferior frontal gyrus was the result of evaluation of the grapheme-to-phoneme correspondence (GPC). Similar results have also been reported by researchers of other languages such as French (Joubert et al., 2004), and Spanish (Carreiras et al., 2006). However, activation of the middle frontal gyrus by low-frequency stimuli has been reported by Chinese researchers (Kuo et al., 2003; Lee et al., 2004; Peng et al., 2004).

These studies show that the left middle frontal gyrus is the brain area specific for processing Chinese, but its origin and mechanism still requires further clarification. The current study found that Chinese early acquired words were, consistent with alphabet writing, also processed in the left inferior frontal gyrus. The differences between Chinese character and alphabetic writing come appear when examining late acquired words that including low-frequency words, written words, late second languages (L2), and other such examples. The differences manifest in the following way: Chinese late words are processed in the left middle frontal gyrus, and the alphabetic writing of late words is processed in the left inferior frontal gyrus.

As for the mechanism of Chinese processing, we speculate the differences in brain areas processing Chinese character and alphabetic writing depend on the characteristics of the syllable if phoneme components are contained in the words. Phonemes without meaning can be separated with semantics, so the processing of phonemes is separated into the temporal lobe to reduce the burden on the inferior frontal gyrus. In languages such as English, single syllables mainly take the form of consonant plus vowel plus consonant, and the phonology of consonants and vowels do not make any sense. To reduce the burden on the inferior frontal gyrus, phoneme components of late acquired alphabetic writing are segregated to the temporal lobe for processing. Chinese characters belong to a syllable character, and the form of the syllables is consonant plus vowel. There is no consonant at the end. Syllables express

semantics, and syllables and semantics are closely and inseparably, combined. Semantics are processed in the frontal lobe, where phonology is also processed and not segregated to the temporal lobe. Chinese speakers reduce the burden on the inferior frontal gyrus by establishing a language-processing region in the middle frontal gyrus outside of the inferior frontal gyrus. Thus, late acquired Chinese words, low-frequency words, and the syllables and semantics of single words of written language are processed in the middle frontal gyrus, rather than the temporal lobe. The temporal lobe does not participate in the processing network for single Chinese words.

Early and late acquired Chinese words are not processed in the same brain area, and this characteristic facilitates the study of separating brain areas by the age of processing. However, these issues need more in-depth research in the future.

Additionally, the present study proves that the processing networks for Chinese and alphabetic writing are different. Alphabetic writing depends on a frontal-parietal network or a frontal-temporal network, while Chinese characters rely on a left frontal-right hemisphere network.

As shown by the correlation analysis, the right superior frontal gyrus activated in high-frequency Cantonese word tasks is highly correlated with the left inferior frontal gyrus. In high-frequency Mandarin word tasks, the activations of the left middle frontal gyrus and the right medial prefrontal lobe are highly correlated. In low-frequency conditions, the functional connectivity is consistent for both languages and shows a high correlation between the left middle frontal gyrus and the right medial prefrontal lobe.

Regarding the right hemisphere issues in Chinese processing, early behavioral researches discussed the function of the right hemisphere in Chinese character processing. Yang Biao et al. (1989) explored the characteristics of functional activation of both hemispheres in Chinese-English bilinguals identifying Chinese characters and English words. The findings showed that Chinese students and foreign students had a two hemisphere advantage in Chinese character identification, but foreign teachers (monolinguals) only had a left hemisphere advantage. The authors speculated this was due to the order of information processing for Chinese characters, which can be the following: orthographic→ phonologic→ semantic; or orthographic→ semantics. A study by Hu Biyuan et al. (1989) found that the processing of Chinese characters and alphabetic writing in children from 7-11 years showed a left hemisphere advantage, but both hemispheres balanced after 11 years old. Behavioral researchers have put forward a two hemisphere processing theory for Chinese characters, but they could not confirm which brain regions in those two hemispheres are involved processing of Chinese characters because of the limitations of behavioral methods. fMRI studies have demonstrated that language stimuli simultaneously activate many brain regions in both hemispheres (Hampson et al., 2002; Li et al., 2004; Ramnani et al., 2004). Ma Lin et al. (2002) found that the activated regions were mainly focused in the left hemisphere when subjects preformed synonymy character or Chinese character homophone judgment tasks. These areas include Broca's and Wernicke's areas, and activity signals were also present in corresponding areas of the inferior frontal cortex and superior temporal gyrus of the right hemisphere. These studies did not explain the specifics of the relationship between the brain areas of the right hemisphere and the language processing regions of the left hemisphere or the contribution to the network processing. The current study not only expounded which specific brain regions are connected between the left and right hemisphere, but also confirmed the levels of connectivity.

5. Conclusion

As above discussed, we came to following conclusion: the left inferior frontal gyrus is biased to processing early acquired words, while the left middle frontal gyrus is biases toward processing late acquired words. Late acquired words include low-frequency words, written words, late L2 words, etc. AOA is the main basis upon which these brain regions are divided. Related statistical results show that the processing network for Chinese single words is a left frontal-right hemisphere network that does not include the participation of the temporal lobe, and processing of Chinese phonology needs the interaction and cooperation of both hemispheres. What's more, our findings prove that the phonology is the foundation of distinguishing different languages. A study, based on the Arabic numbers, demonstrated differential cortical representation of numbers between native Chinese and English speakers (Tang et al., 2006). However, when it comes to languages, does it still the same story? Our study found low-frequency Cantonese and Mandarin words both activated the left middle frontal gyrus and right medial prefrontal lobe, but the networks were not consistent. To know more about the languages distinction, further studies are needed.

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Author Introduction

Author1: Yaqiong Xiao; She is postgraduate from College of Education, Guangzhou University, R. P. China; Her research interest is cognitive processing of language, resting-state fMRI, the development of language networks in children.

Author2: Hongchang Zhai; He is professor at College of Education, Guangzhou University, R. P. China; His research interests include cognitive processing of language, cognitive mechanisms underlying dialect and Mandarin; resting-state fMRI, the development of language networks in children.

Author3: Xiaoxia Xu; She is postgraduate from College of Education, Guangzhou University, R. P. China; Her research interest is cognitive processing of language.